

## APPENDIX A

% BEGINNING OF PSEUDO CODE

5       % compute scale factor A, and time constants a, b from physical system  
      % parameters

$A = V_{\max} * K_t / (R_e * R_m + K_t * K_b) * 1 * k;$

10     $p1 = 1/J_m/I_e * (-I_e * R_m - R_e * J_m + \sqrt{I_e^2 * R_m^2 - 2 * R_e * R_m * I_e * J_m}$   
       $+ R_e^2 * J_m^2 - 4 * K_t * K_b * I_e * J_m}) / 2;$   
       $p2 = 1/J_m/I_e * (-I_e * R_m - R_e * J_m - \sqrt{I_e^2 * R_m^2 - 2 * R_e * R_m * I_e * J_m}$   
       $+ R_e^2 * J_m^2 - 4 * K_t * K_b * I_e * J_m}) / 2;$

15        $a = \max(-p1, -p2)$   
       $b = \min(-p1, -p2)$

% make initial guesses for step durations

20        $et1 = 1;$   
       $et2 = .005;$   
       $et3 = 1;$

% set maximum iteration count

25        $N_{\max} = 1000;$

for  $j = 1:N_{\max}$

% save old values of step time intervals

30        $et3_{\text{old}} = et3;$

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et2old = et2;
et1old = et1;

% iterate for switch times using fixed voltage level Vmax

5
et3 = -log(1.0 / 2.0 - exp(-et1 * a) / 2 + exp(-et2 * a)) / a;
et2 = 1/b * log(2.0) + 3 * et3 - 1/b * log(2 * exp(1/A * b * X) * exp(et3
    * b) - sqrt(4.0) * sqrt(exp(1/A * b * X)) * exp(et3 * b) *
    sqrt(exp(1/A * b * X)+exp(et3 * b)^2 - 2 * exp(et3 * b)));
10
et1 = - (-2 * A * et2 + 2 * A * et3 - X) / A;

if norm([et3old - et3 et2old - et2 et1old - et1], inf) <= eps * 2
    break
end
15
if j==Nmax
    error(['error - failure to converge after ', num2str(Nmax),'
        iterations'])
end
end

20

% round up pulse duration to nearest sample interval,
% convert to intervals between steps to make sure that voltage
% requirements will not increase (beyond Vmax).

25
dt1=ceil((et1 - et2) / dt) * dt;
dt2=ceil((et2 - et3) / dt) * dt;
dt3=ceil((et3) / dt) * dt;

et123 = [et1, et2, et3]

30
% convert back to total step duration.

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$$et1 = dt1 + dt2 + dt3;$$

$$et2 = dt2 + dt3;$$

$$et3 = dt3;$$

5       % In the following, the original constraints equations involving XF1, XF2,  
       % and XF3 have been modified to include a variable voltage level applied

at

      % each step (instead of the fixed maximum (+/-) Vmax).

10       % The original equations for XF1, XF2, and XF3 follow:

$$\% \quad XF_1(t_{end}) = V_0 F_1(t_{end} - t_0) - 2V_0 F_1(t_{end} - t_1) + 2V_0 F_1(t_{end} - t_2)$$

$$\% \quad XF_2(t_{end}) = V_0 F_2(t_{end} - t_0) - 2V_0 F_2(t_{end} - t_1) + 2V_0 F_1(t_{end} - t_2)$$

$$\% \quad XF_3(t_{end}) = V_0 F_3(t_{end} - t_0) - 2V_0 F_2(t_{end} - t_1) + 2V_0 F_1(t_{end} - t_2)$$

15       % And the modified equation including adjustable relative levels of  
       voltage

      % L1, L2 and L3 are:

$$\% \quad XF_1(t_{end}) = L_1 V_0 F_1(t_{end} - t_0) - L_2 V_0 F_1(t_{end} - t_1) + L_3 V_0 F_1(t_{end} - t_2)$$

$$\% \quad XF_2(t_{end}) = L_1 V_0 F_2(t_{end} - t_0) - L_2 V_0 F_2(t_{end} - t_1) + L_3 V_0 F_1(t_{end} - t_2)$$

20       %  $XF_3(t_{end}) = L_1 V_0 F_3(t_{end} - t_0) - L_2 V_0 F_2(t_{end} - t_1) + L_3 V_0 F_1(t_{end} - t_2)$

      % And the corresponding constraint equations are:

$$\% \quad XF_1(t_{end}) = Finalpos$$

$$\% \quad XF_2(t_{end}) = 0$$

25       %  $XF_3(t_{end}) = 0$

      % Where all of the times indicated have discrete values, e.g.  
       corresponding to

      % the controller update rate.

30

% It should be noted that after the digital switch times are fixed, the  
constraint

% equations derived from the equations above form a linear set of  
equations in

5 % the unknown relative voltage levels L1, L2 and L3 and any standard  
linear

% method can be used to solve for the relative voltage levels. In the  
equations

% for (L1, L2 and L3) that follow, the solution was obtained by algebraic

10 % means (and are not particularly compact.)

% compute new relative voltage step levels

% L1, L2 and L3 are nominally assigned to "1", "-2" and "+2",  
respectively

15 s1 = X \* (exp(-et3 \* b) \* exp(-et2 \* a) + exp(-et3 \* a) + exp(-et2 \* b) - exp(-et2  
\* b) \* exp(-et3 \* a) - exp(-et2 \* a) - exp(-et3 \* b));

s2 = 1 / (et2 \* exp(-et1 \* b) \* exp(-et3 \* a) + exp(-et2 \* b) \* et3 \*  
exp(-et1 \* a) - et2 \* exp(-et3 \* a) - et2 \* exp(-et1 \* b) - et3 \*  
exp(-et1 \* a) - exp(-et2 \* b) \* et3 + exp(-et3 \* b) \* et1 \* exp(-et2 \*  
20 a) + exp(-et3 \* a) \* et1 + exp(-et2 \* b) \* et1 - exp(-et2 \* b) \* et1 \*  
exp(-et3 \* a) - et3 \* exp(-et1 \* b) \* exp(-et2 \* a) - exp(-et2 \* a) \*  
et1 - exp(-et3 \* b) \* et1 - exp(-et3 \* b) \* et2 \* exp(-et1 \* a) + et3 \*  
exp(-et1 \* b) + et2 \* exp(-et1 \* a) + exp(-et3 \* b) \* et2 + et3 \*  
exp(-et2 \* a)) / A;

25

L1 = s1 \* s2;

s1 = 1 / (et2 \* exp(-et1 \* b) \* exp(-et3 \* a) + exp(-et2 \* b) \* et3 \*  
exp(-et1 \* a) - et2 \* exp(-et3 \* a) - et2 \* exp(-et1 \* b) - et3 \*  
30 exp(-et1 \* a) - exp(-et2 \* b) \* et3 + exp(-et3 \* b) \* et1 \*

```

exp(-et2 * a) + exp(-et3 * a) * et1 + exp(-et2 * b) * et1 -
exp(-et2 * b) * et1 * exp(-et3 * a) - et3 * exp(-et1 * b) *
exp(-et2 * a) - exp(-et2 * a) * et1 - exp(-et3 * b) * et1 - exp(-et3 *
b) * et2 * exp(-et1 * a) + et3 * exp(-et1 * b) + et2 * exp(-et1 * a) +
5      exp(-et3 * b) * et2 + et3 * exp(-et2 * a)) * X;
s2 = (exp(-et2 * b) * exp(-et1 * a) - exp(-et1 * a) - exp(-et2 * b) -
      exp(-et1 * b) * exp(-et2 * a) + exp(-et1 * b) + exp(-et2 * a)) / A;
L3 = s1*s2;

10  s1 = exp(-et1 * a) - exp(-et3 * a) + exp(-et3 * b) - exp(-et1 * b) -
      exp(-et3 * b) * exp(-et1 * a) + exp(-et1 * b) * exp(-et3 * a);
s2 = X / (et2 * exp(-et1 * b) * exp(-et3 * a) + exp(-et2 * b) * et3 *
      exp(-et1 * a) - et2 * exp(-et3 * a) - et2 * exp(-et1 * b) - et3 *
      exp(-et1 * a) - exp(-et2 * b) * et3 + exp(-et3 * b) * et1 * exp(-et2 *
15  a) + exp(-et3 * a) * et1 + exp(-et2 * b) * et1 - exp(-et2 * b) * et1 * exp(-
et3 * a) - et3 * exp(-et1 * b) * exp(-et2 * a) - exp(-et2 * a) * et1 - exp(-et3 *
b) * et1 - exp(-et3 * b) * et2 * exp(-et1 * a) + et3 *
      exp(-et1 * b) + et2 * exp(-et1 * a) + exp(-et3 * b) * et2 + et3 *
      exp(-et2 * a)) / A;

20
L2 = s1 * s2;

% convert accumulated voltage steps to sequential voltage level
V1 = Vmax * (L1);
25  V2 = Vmax * (L1 + L2);
V3 = Vmax * (L1 + L2 + L3);

% END OF PSEUDO CODE

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## APPENDIX B

AREA .. SUM(I,A(I)) =E= 0;  
VELOCITY(VINDEX) .. VEL(VINDEX) =E= VSCALE \*

5 SUM(I\$(ORD(I) LE ORD(VINDEX)), A(I));  
POSITION .. SUM(I,VEL(I)) =E= FINALPOS \* SCALEFACT;  
VLIMITP(I) .. SUM(VINDEX\$(ORD(VINDEX) LE ORD(I)),A(I-  
(ORD(VINDEX)+1))\*(VOLTS(VINDEX)+KBACK\*VSCALE))  
=L= VOLTLM;  
10 VLIMITN(I) .. SUM(VINDEX\$(ORD(VINDEX) LE ORD(I)), A(I-  
(ORD(VINDEX)+1))\*(VOLTS(VINDEX)+KBACK\*VSCALE))  
=G= -VOLTLM

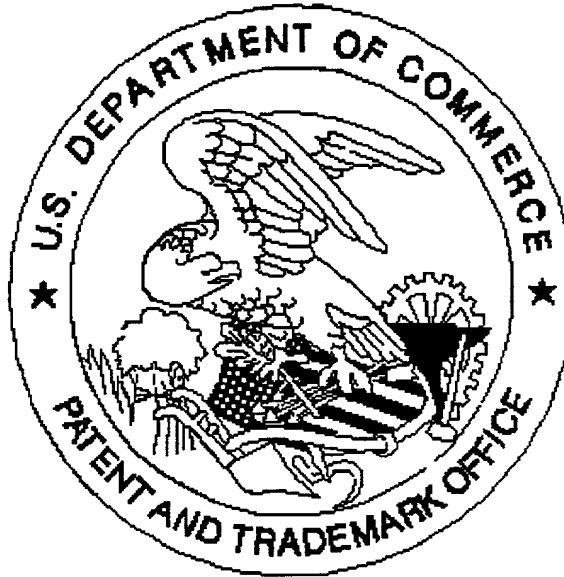
% A(I) are the current commands at time T(I) spaced equally at time DT.  
15 % VOLTS(VINDEX) is a table of voltages representing the unit pulse  
response to  
% a unit output in current command. VOLTLM is the voltage limit at  
saturation.

## APPENDIX C

GOALPOS .. SUM(I,A(I)\*MODELAA\*DT) =E=FINALPOS;  
MODE1(ILAST) .. SUM(I,-A(I)\*MODELAA\*MODELb/(MODELb-  
5     MODELa)\*(EXP(-MODELa\*(T(ILAST)+DT-T(I)))  
      -EXP(-MODELa\*(T(ILAST)-T(I)))) =E= 0.0;  
MODE2(ILAST) .. SUM(I,A(I)\*MODELAA\*MODELa/(MODELb-  
      MODELa)\*(EXP(-MODELb\*(T(ILAST)+DT-T(I)))  
      -EXP(-MODELb\*(T(ILAST)-T(I)))) =E= 0.0;  
10    DERIV1(J) .. 1000.0\*SUM(I,A(I)\*T(I)\*EXP(ZETA(J)\*W(J)\*T(I))\*  
      SIN(WD(J)\*T(I))) =E= 0.0 ;  
      DERIV2(J) .. 1000.0\*SUM(I,A(I)\*T(I)\*EXP(ZETA(J)\*W(J)\*T(I))\*  
      COS(WD(J)\*T(I))) =E= 0.0 ;  
  
15     % MODELAA is the mechanical gain of the system, MODELb, and MODELa  
      % are the two time constants of the system in radians. One time constant is  
      % associated with the L/R rise time of the motor inductance and the other is  
      % the mechanical time constant of the rigid system. The A(I) are the voltages %  
      which need to be determined. The T(I) are the times for each of the A(I).  
20     % DT is the time spacing of the outputs. W(J) are the undamped flexible  
      % modes, WD(J) are the damped flexible modes (in radians/s).

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